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Original Article

Successive measurement errors of consecutive computed tomography for airway-related craniofacial dimensional measurements

Jui-Sheng Sun [a,b†], Shih-Ying Lin [c†], Chi-Yeh Hsieh [d], Min-Chih Hung [e], Han-Cheng Tai [a], Jenny Zwei-Chieng Chang [d,e*]

[a] *Department of Orthopedic Surgery, En Chu Kong Hospital, New Taipei City, Taiwan*
[b] *Department of Orthopedic Surgery, National Taiwan University Hospital, Taipei, Taiwan*
[c] *Department of Dentistry, MacKay Memorial Hospital, Taipei, Taiwan*
[d] *School of Dentistry, College of Medicine, National Taiwan University, Taipei, Taiwan*
[e] *Department of Dentistry, National Taiwan University Hospital, Taipei, Taiwan*

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Abstract *Background/purpose:* The use of computed tomography (CT) for craniofacial measurements is common in medical imaging, but concerns about accuracy and reliability persist, especially with different CT technologies. This study assessed the accuracy of twenty-six common measurements on consecutive CT images from the same patients, using multidetector CT (MDCT) and cone-beam CT (CBCT) with two software programs (Amira and Dolphin).
Materials and methods: Ten adult subjects with consecutive CBCT scans within one year were randomly selected. Another ten subjects with consecutive MDCT scans were paired with the CBCT group based on age, gender, race, occlusion, and craniofacial pattern. All digital imaging and communications in medicine (DICOM) files were randomly coded and analyzed using the two software programs. Intra-examiner reliability was assessed using the intraclass correlation coefficient. Successive measurement errors from consecutive scans for both imaging modalities and software programs were compared.
Results: For most skeletal linear and angular measurements, Dolphin showed greater successive measurement errors compared to Amira. Eight of the 26 common measurements had errors greater than one unit (millimeter or degree). Despite almost perfect intra-examiner reliability for upper airway analysis, average successive measurement errors were notably high, particularly for intraoral and oropharyngeal airway volumes. The successive Dolphin measurement error for oropharyngeal airway volume on CBCT images was over three times that on MDCT images.

* Corresponding author. School of Dentistry, College of Medicine, National Taiwan University, No 1, Chang-De Street, Taipei 10048, Taiwan.
E-mail address: jennyzc@ms3.hinet.net (J.Z.-C. Chang).
† Contribute equally as the first authors in this work.

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Conclusion: Given the substantial successive measurement errors observed during consecutive CT scanning for the upper airway, this study does not support the quantitative use of CT for analyzing changes in airway dimensions for research purposes.

Introduction

Hounsfield and Cormack invented computed tomography (CT) in the early 1970s, ushering medical imaging from two-dimensional (2D) into the three-dimensional (3D).[1] Modern CT technology integrates fan-shaped beam, helical/spiral synchronous motion, and multiple rows of detectors, producing high-quality images in very short acquisition time.[2] However, due to the high equipment cost and radiation dose, clinical applications of multidetector CT (MDCT) or multi-slice CT (MSCT) in dentistry have been limited. In the late 1990s, cone-beam CT (CBCT) was developed with a cone-shaped x-ray source and detector fixed on a rotating platform. Unlike MDCT, which scans subjects in a supine position, CBCT advancements have allowed for imaging patients in an upright position. CBCT is now widely used for pre-operative planning of dental implant placement, orthodontics, and oral and maxillofacial surgery. Additionally, CBCT has applications in vascular imaging, otorhinolaryngology, radiotherapy, and mammography.[2]

With the involvement of orthodontists and oral maxillofacial surgeons in treating obstructive sleep apnea (OSA), CBCT has been increasingly used for 3D assessment of the upper pharyngeal airway. Despite its growing popularity in airway research, studies have shown the inaccuracy and unreliability of CBCT airway measurements.[3,4] Although the radiation dose of CBCT is less than that of MDCT, it is still higher than traditional dental panoramic or cephalometric radiographic exposures. The relatively high cumulative doses and associated cancer risk are particularly concerning for pediatric population,[5] necessitating a justification for routine CBCT exposures for research purposes. MDCT differentiates tissue based on accurate and absolute Hounsfield unit (HU) value; whereas CBCT lacks satisfactory gray scale sensitivity to discriminate between fluids and different soft tissues.[2] Unlike MDCT, which provides fixed HU for specific tissue, CBCT gray value inaccuracies stem from variability between axial slices, high image noise, and variability in the axial plane. Despite identical densities, different gray values appear at different positions within the CBCT scan,[6] questioning the quantitative use of gray values in CBCT.

A soft tissue equivalent phantom study showed that CBCT measurement of holes in the phantom were accurate,[7] implying CBCT's capability of defining boundaries between air and soft tissue. Several studies have compared the accuracy of dimensional measurement between CBCT and MDCT in the craniofacial regions using human cadaver/skull or phantom/prototype. These studies mostly showed statistically insignificant difference between physical linear measurements and on 3D CT surface rendering or cross-sectional images.[8–10] However, other studies reported significant difference between MDCT and CBCT for linear,[11] volumetric, and cross-sectional area measurements.[12] For example, Naser and Mehr reported significant difference between MDCT and CBCT for the linear measurements of six distances at each of seven sections on ten hemi-mandible specimens.[11] Whereas, Chen et al. reported significant differences in the volumetric and cross-sectional area measurements of an anthropomorphic oropharyngeal phantom with known dimensions using different MDCT and CBCT scanners.[12] As these studies were performed on motionless objects, the reported accuracy of CBCT measurements might be overrated. The acquisition time of CBCT for the entire craniofacial structure can take 20–40 s, increasing the chance of patient-motion artifacts; while MDCT scanning takes only about a second. A systematic review of 42 clinical studies reported moderate to excellent reliability of CBCT in quantitatively measuring the airway, but none of the examiners were allowed to manually orient the scanned images or select threshold sensitivity.[13] The final upper airway segmentation volume is affected by CT device settings, imaging quality, threshold interval selection, and segmentation algorithms of the imaging software.[14,15] Other patient-related factors such as patient positioning, breathing stage, and head and tongue posture may also influence airway volume.[15,16] Collectively, the reliability of CBCT dimensional measurements remains unclear due to methodological limitations of previous studies.

Considering the inherent weaknesses of CBCT technology, the risk of cumulative radiation doses, the impact of patient motion, it is necessary to investigate the accuracy of airway-related dimensional measurements on consecutive CT scans to justify multiple CBCT exposures for research purposes. This study aimed to assess the accuracy of twenty-six common measurements on consecutive CT-generated tomographic multi-planar reformatted (MPR) slices, 2D virtual lateral cephalometric projections, and 3D surface- and volume-rendered images from the same patients acquired by MDCT and CBCT (two protocols) at two time points using two software programs (Amira and Dolphin). The primary aim was to highlight the limitations and inaccuracies associated with 3D airway measurements, particularly in the context of CT imaging.

Materials and methods

Subject screening

With approval from the Research Ethics Committee of National Taiwan University Hospital (number: 202201101RINA), patients who had undergone two consecutive CT scans of the head and neck between 2016 and 2021 were retrieved from the National Taiwan University Hospital-integrative Medical Database (NTUH-iMD). The inclusion criteria were: adult patients who had received consecutive CBCT or MDCT/MSCT head and neck scans with a scan interval of less than one year and no treatment of the head and neck region between the two scans. The settings of MDCT and CBCT devices are given in Table 1. The exclusion criteria were: images that did not contain the entire craniofacial portion, head and neck treatment that could have affected the measurements between the two scan intervals, patient age younger than 20-year-old, teeth not occluded at maximum intercuspation, or images acquired using devices or settings other than those listed in Table 1. Patients who had received two consecutive CBCT or MDCT scans were designated as the CBCT or MDCT group, respectively. Power analysis revealed that a sample size of ten subjects per group was needed (two-sided $\alpha = 5\%$, power 80%). Ten patients were randomly selected from twenty-seven patients and designated as the CBCT group. Ten patients were designated as the MDCT group and were pair-matched to the CBCT group for age, gender, race, occlusion, and craniofacial pattern. The screening flow chart is detailed in Fig. 1.

Randomization of the DICOM files

After case selection, all scanned images were reconstructed and exported as digital imaging and communications in medicine (DICOM) files. The forty DICOM files ([10 MDCT patients + 10 CBCT patients] x two time points) were randomly coded by the author JZC. One senior orthodontic resident (C-YH) was asked to import these DICOM files into two software programs, Amira (version 2022.1, Thermo Fischer Scientific, Merignac, France) and Dolphin Imaging Version 11.9 Premium (Dolphin Imaging and Management Solutions, Chatsworth, CA, USA). The resident was asked to treat these files as independent data, not knowing which data was the successive data from the same patient or the image modality (MDCT or CBCT).

Image processing and dimensional measurements

After importing the CT data into Amira or Dolphin software, the resident was informed to reorient the head position following a step-by-step handout with illustrations. In brief, the Frankfort horizontal (FH) plane (as axial plane) was placed parallel to the global horizontal plane, the frontal plane passing through the buccal groove of the right maxillary first molar and perpendicular to FH plane, and the sagittal plane passing through the glabella while perpendicular to both axial and frontal planes. Before measurement, HU calibration/correction was carried out with Amira but not Dolphin (calibration function not available for Dolphin). Eight linear measurements were performed on the tomographic multi-planar reformatted slices: (1) anterior nasal width (ANW),[17,18] (2) anterior nasal floor width (ANFW),[17,18] (3) posterior nasal width (PNW),[17,18] (4) posterior nasal floor width (PNFW),[17,18] (5) external maxillary width (EMW),[19] (6) palatal width (PW),[19] (7) intermolar width at the first molar palatal apex level (Inter-Mpa),[19] and (8) intermolar width at the first molar central fossa level (Inter-Mcf).[19] Six linear measurements were performed on the 3D surface rendering images: (1) zygomaticotemporal suture upper right to left (ZTUr-l),[20] (2) frontomaxillary suture right to left (FMr-l),[21,22] (3) frontozygomatic right to left (FZr-l),[21] (4) inner nasal contour point right to left (INCr-l),[20] (5) zygomatico-maxillary upper right to left (ZMUr-l),[20] and (6) zygomatico-maxillary lower right to left (ZMLr-l).[20] Six parameters were measured on the CT-derived lateral cephalometric projections: (1) Sella-Nasion-subspinale angle (SNA), (2) Sella-Nasion-supramentale angle (SNB), (3) Sella-Nasion-Gonion-Gnathion angle (SNGoGn), (4) spinal curvature (Lordosis angle; L),[23] (5) Condylion to Point A [Co-A], and (6) Condylion to Gnathion [Co-Gn]). Six parameters were measured for upper airway analysis (1) total oropharynx height (TOH),[24] (2) intraoral airway volume (IAV),[25] (3) nasopharyngeal airway volume (NAV),[24] (4) oropharyngeal airway volume (OAV),[24] (5) hypopharyngeal airway volume (HAV),[24] and (6) minimum cross-sectional area in the oropharynx (MCA).[24] These were 26 common variables used in airway-related research. After the upper, lower, front, and rear boundaries were set and the airway threshold sensitivity selected, the software automatically calculated the airway dimension. Prior to conducting this study, the resident practiced these measurements on a different set of duplicated samples with random coding consisting of five patients that received both MDCT and CBCT scanning. His intra-examiner reliability estimated by intraclass correlation coefficient (ICC) values for repeated measurements using Amira was 0.964∼0.999 on MDCT images and 0.965∼0.999 on CBCT images for the 26 variables (Appendix Table).

Table 1 The settings of the multidetector computed tomography (MDCT) and cone-beam computed tomography (CBCT) devices used in this study.

Type	Model	Manufacturer	Tube voltage	Tube current	FOV	Voxel size	Exposure time	Patient positioning
MDCT	Somatom Definition AS	Siemens Medical Solutions, Malvern, PA, USA	120 kVP	260 mA	512 × 512 (matrix size)	1.2 mm (slice thickness)	0.5 s	supine
CBCT	3D Accuitomo 170	J. Morita MFG. Corp., Kyoto, Japan	90 kVP	5 mA	17 × 12 cm	0.25 mm	17.5 × 2 = 35 s[a]	upright

Abbreviations: CBCT, cone-beam computed tomography; cm, centimeter; FOV, field of view; kVP, Kilovolts Peaks; mA, milliampere; MDCT, multidetector computed tomography; mm, millimeter.
[a] Two consecutive scans acquired and the upper and lower images were stitched into one image.

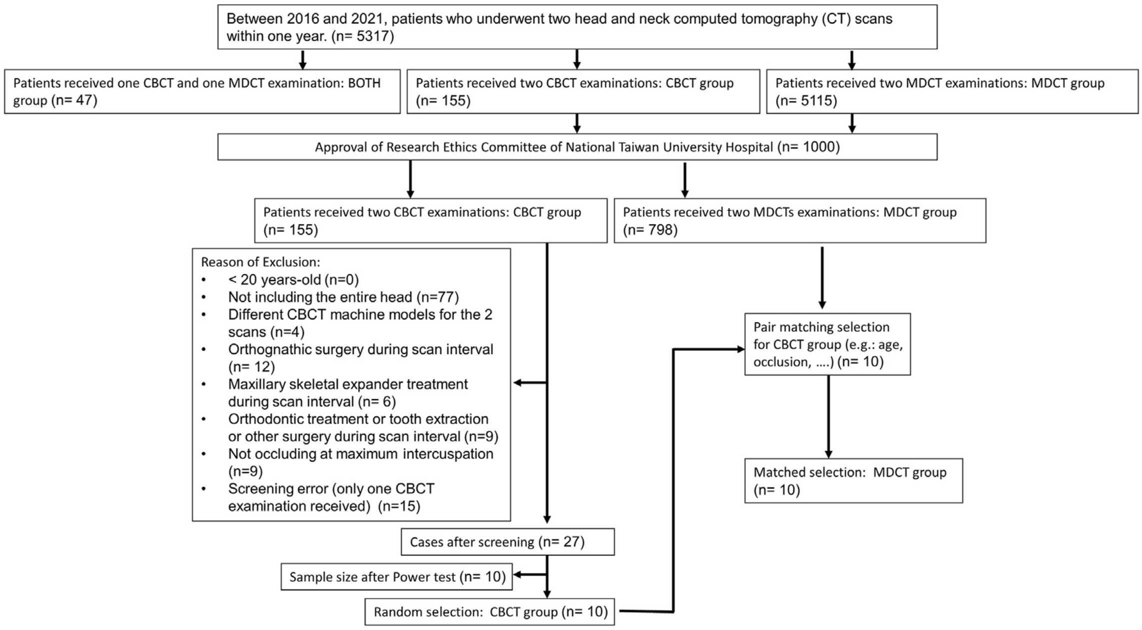

Figure 1 Detailed flow chart of subject screening.

Statistical analysis

Statistical analysis was performed and scatterplots were generated using R statistical software version 4.2.3 (https://www.r-project.org). The absolute value of the difference between measurements of the same patient for the two time points was considered the 'successive measurement error' generated from consecutive scanning. The measurement error between the two imaging modalities (MDCT versus CBCT) and software programs (Amira versus Dolphin) were compared using Wilcoxon sign rank test. The level of significance was set at 0.05.

Results

Demographic data of the subjects

Demographic statistics of the subjects are shown in Table 2. Subjects in the MDCT and CBCT groups were well-matched regarding age, gender, race, occlusion, and skeletal pattern.

Table 2 Demographic data of the subjects.

		Multidetector computed tomography (MDCT) group	Cone-beam computed tomography (CBCT) group
Number of subjects (n)		10	10
Gender	Male (number)	5	5
	Female (number)	5	5
Average age (year-old)		28.67 ± 2.76	27.36 ± 3.47
Occlusion	Class I (number)	2	2
	Class II (number)	2	2
	Class III (number)	6	6
	Overbite (millimeter, mm)	1.67 ± 0.31	1.76 ± 0.29
	Overjet (millimeter, mm)	1.59 ± 0.52	0.91 ± 0.46
Skeletal pattern	Sella-nasion-subspinale angle (SNA) (degree)	83.66 ± 4.92	81.84 ± 1.79
	Sella-nasion-supramentale angle (SNB) (degree)	80.59 ± 4.89	80.63 ± 4.85
	Sella-nasion-gonion-gnathion angle (SN-GoGn) (degree)	32.09 ± 6.94	34.15 ± 4.71

Comparisons of successive measurement error between MDCT and CBCT

The comparisons of successive measurement errors for the two consecutive scanning on MDCT and CBCT images are shown in Table 3 and Appendix Figure. When using Amira, the successive measurement errors of Inter-Mcf and TOH were significantly different between the MDCT and CBCT scans (Table 3 left). All linear and angular successive measurement errors were less than 1 unit (millimeter or degree) except for the Lordosis angle, which had successive measurement errors of more than 5° regardless of the image modality when measured using Amira. All successive measurement errors for the airway volumetric and area variables appeared to be extremely large. When using Dolphin, the successive measurement errors of Inter-Mcf, INCr-l, and OAV were significantly different between MDCT and CBCT scans (Table 3 right). Several linear and angular successive measurement errors were greater than 1 unit (millimeter or degree) including PNFW, ZTUr-l, FZr-l, ZMUr-l, SNA, SNB, SNGoGn, Lordosis angle, and Co-Gn. The Lordosis angle had approximately 5 degrees of successive measurement errors regardless of the image modality when measured using Dolphin. The average measurement errors during consecutive scanning were exceptionally large especially for the variable OAV; where the errors could be as great as 6097.1 ± 4616.69 mm^3 when measuring CBCT images using Dolphin, more than threefold compared to MDCT images (1793.1 ± 1043.83 mm^3).

Comparisons of successive measurement error between Amira and Dolphin

The comparisons of successive measurement errors for the two consecutive scans using Amira or Dolphin imaging software are shown in Table 4 and Appendix Figure. For consecutive MDCT images, variables ANW, ANFW, PNW, PNFW, EMW, ZTUr-l, FZr-l, INCr-l, ZMUr-l, SNA, SNB, and SNGoGn showed statistically significant greater successive measurement errors when measured using Dolphin compared with Amira (Table 4 left). For consecutive CBCT images, variables ANW, PNW, Inter-Mpa, FZr-l, Co-Gn, and OAV showed statistically significant greater successive measurement errors when measured using Dolphin compared with Amira (Table 4 right). The average measurement errors on CBCT for the variable OAV was approximately twofold greater when measured using Dolphin (6097.1 ± 4616.69 mm^3) compared with Amira (3574 ± 3589.29 mm^3).

Discussion

Many interventions have been proposed for the treatment of OSA.[26,27] Recent literature shows increasing interest in using CBCT to assess airway morphology/dimension and its relationship with sleep-disordered breathing or OSA within the maxillofacial and otorhinolaryngological specialties. For example, study has reported that improvement in airway volume correlate with reductions in the apnea-hypopnea index in children undergoing adenotonsillectomy.[28] Despite claiming statistically significant differences in treatment outcomes, these clinical studies, typically reported changes in airway volume with very large standard deviations relative to the mean.[29–31] Iwasaki T et al. reported an average decrease in IAV from 1212.9 ± 1370.9 mm^3 to 279.7 ± 472.0 mm^3 following rapid maxillary expansion (RME), concomitantly with an increase in OAV from 3054.9 ± 1633.4 mm^3 to 4656.3 ± 1607.2 mm^3, suggesting that RME elevates tongue posture and enlarges the pharyngeal airway.[31] Our results show that despite near-perfect intra-examiner reliability for airway analysis using Amira (Appendix Table; ICCs 0.998∼0.999), the average measurement error on consecutive CBCT images for OAV was 6097.1 ± 4616.69 mm^3 with Dolphin. Regardless of the image modality or software, IAV proved exceptionally unreliable with successive measurement errors ranging from 4808.25 ± 5289.96 mm^3 to 6096.82 ± 3862.18 mm^3 (Fig. 2 and Table 3). Since the successive measurement errors could be as great as the treatment effects reported in previous studies, a careful interpretation of CBCT volumetric data to correlate with clinical outcome is necessary.

Using an anthropomorphic head phantom, recent study demonstrated that different CBCT imaging positions could affect the accuracy and completeness of the 3D models.[32] Hassan et al. showed a statistically significant difference between the ideal and rotated positions for the cephalometric images, while measurements on 3D surface images were relatively accurate. However, the change of position in that study was a rotation around the Z axis only.[33] Clinically, a patient's head position may change in all X, Y, and Z axes. Our study showed that successive measurement errors of several linear and angular variables of the craniofacial skeleton exceeded 1 unit. Coppelson et al. demonstrated that an increase of cranial-cervical extension by 5° could result in a 25% increase in MCA; while a 5° decrease resulted in a 21% decrease.[34] In our study, the mean change in lordosis angle between two time points was approximately 5°, regardless of the image modality or software program. This altered head posture could be an important factor causing differences between measurements of consecutive CT images. Pae et al. compared upright and supine cephalograms of OSA patients and showed that oropharyngeal area decreased 36.5% in supine position.[35] Our study similarly demonstrated reduced OAV (Fig. 3) and MCA (Fig. 4) in the supine MDCT images compared with the upright CBCT images.

Dolphin is a popular software program among orthodontists and surgeons due to its user-friendly interface. It offers a variety of tools to help doctors capture, store, and analyze dental images, and it also includes orthognathic surgical simulation capabilities. Its popularity is further enhanced by its rapid upper airway segmentation, high segmentation sensitivity, and the ability to analyze the minimum cross-sectional area airway.[14] However, it is unable to correct or adjust airway segmentation in 2D slices and its threshold interval units are not compatible with other imaging software. De Water et al. compared the airway volumes of oral pharynx and nasal passage measured using semiautomatic segmentation by Dolphin and manual segmentation by MevisLab on MDCT scans of 20 patients with syndromic craniosynostosis and found that Dolphin

Table 3 Comparisons of successive measurement error between multidetector computed tomography (MDCT) and cone-beam computed tomography (CBCT).

		The mean absolute difference between the two consecutive scans					
		Amira x MDCT	Amira x CBCT	Wilcoxon signed rank test	Dolphin x MDCT	Dolphin x CBCT	Wilcoxon signed rank test
	Variable	Mean ± S.D.	Mean ± S.D.	*P* value	Mean ± S.D.	Mean ± S.D.	*P* value
Linear measurements on the tomographic multi-planar reformatted slice	ANW (mm)	0.6 ± 0.25	0.5 ± 0.32	0.342	0.85 ± 0.37	0.9 ± 0.37	0.635
	ANFW (mm)	0.37 ± 0.21	0.55 ± 0.32	0.183	0.79 ± 0.5	0.93 ± 0.48	0.575
	PNW (mm)	0.34 ± 0.19	0.35 ± 0.25	1	0.95 ± 0.45	0.65 ± 0.26	0.126
	PNFW (mm)	0.52 ± 0.2	0.36 ± 0.37	0.109	1 ± 0.46	0.71 ± 0.28	0.275
	EMW (mm)	0.35 ± 0.2	0.52 ± 0.44	0.441	0.92 ± 0.59	0.8 ± 0.54	0.61
	PW (mm)	0.54 ± 0.34	0.5 ± 0.22	0.622	0.75 ± 0.38	0.63 ± 0.4	0.678
	Inter-Mpa (mm)	0.55 ± 0.38	0.32 ± 0.23	0.185	0.89 ± 0.63	0.87 ± 0.45	0.959
	Inter-Mcf (mm)	0.21 ± 0.17	0.49 ± 0.26	0.022*	0.39 ± 0.28	0.64 ± 0.34	0.096*
Linear measurements on the three-dimensional surface rendering images	ZTUr-l (mm)	0.57 ± 0.18	0.48 ± 0.27	0.358	1.08 ± 0.56	0.82 ± 0.52	0.441
	FMr-l (mm)	0.36 ± 0.24	0.35 ± 0.16	0.959	0.52 ± 0.29	0.59 ± 0.33	0.683
	FZr-l (mm)	0.33 ± 0.22	0.43 ± 0.23	0.331	1.2 ± 0.5	1.03 ± 0.53	0.22
	INCr-l (mm)	0.47 ± 0.2	0.31 ± 0.2	0.151	0.96 ± 0.37	0.52 ± 0.41	0.041*
	ZMUr-l (mm)	0.62 ± 0.39	0.72 ± 0.29	0.77	1.08 ± 0.15	0.9 ± 0.58	0.275
	ZMLr-l (mm)	0.7 ± 0.32	0.66 ± 0.22	0.592	0.93 ± 0.23	0.95 ± 0.5	0.906
Measurements on the computed tomography-derived lateral cephalometric projections	SNA (degree)	0.5 ± 0.35	0.58 ± 0.35	0.813	1.23 ± 0.93	0.69 ± 0.38	0.092
	SNB (degree)	0.68 ± 0.47	0.54 ± 0.31	0.61	1.5 ± 1	0.91 ± 0.43	0.084
	SNGoGn (degree)	0.72 ± 0.34	0.53 ± 0.33	0.322	1.14 ± 0.38	0.81 ± 0.5	0.236
	L (degree)	5.54 ± 4.03	5.22 ± 3.29	0.922	5.32 ± 4.34	4.59 ± 3.11	0.846
	Co-A (mm)	0.68 ± 0.16	0.61 ± 0.2	0.514	0.55 ± 0.47	0.65 ± 0.55	0.919
	Co-Gn (mm)	0.65 ± 0.26	0.54 ± 0.3	0.363	0.61 ± 0.48	1.32 ± 0.96	0.126
Airway analysis	TOH (mm)	0.7 ± 0.16	0.42 ± 0.16	0.014*	0.81 ± 0.38	0.7 ± 0.55	0.553
	IAV (mm^3)	5491.75 ± 5322.02	4847.57 ± 3052.86	0.5	4808.25 ± 5289.96	6096.86 ± 3862.18	0.75
	NAV (mm^3)	580.4 ± 548.58	671.4 ± 437.92	0.846	918.6 ± 744.11	1414.2 ± 1295.98	0.375
	OAV (mm^3)	2234.3 ± 2145.96	3574 ± 3589.29	0.275	1793.1 ± 1043.83	6097.1 ± 4616.69	0.014*
	HAV (mm^3)	871 ± 842.44	1490.6 ± 1984.64	0.813	1243.2 ± 959.5	1582.4 ± 1564.7	0.813
	MCA (mm^2)	28.1 ± 22.97	46.9 ± 44.78	0.646	25.9 ± 20.86	57.4 ± 56.63	0.232

*$P < 0.05$ indicates statistical significance.

Abbreviations. ANFW: Anterior nasal floor width; ANW: Anterior nasal width; Co-A: Condylion to Point A; CBCT: cone-beam computed tomography; Co-Gn: Condylion to Gnathion; EMW: External maxillary width; FMr-l: Frontomaxillary suture right to left; FZr-l: Frontozygomatic right to left; HAV: Hypopharyngeal airway volume, IAV: Intraoral airway volume; INCr-l: Inner nasal contour point right to left; Inter-Mcf: Intermolar width at the first molar central fossa level; Inter-Mpa: Intermolar width at the first molar palatal apex level; L: Lordosis angle; MCA: minimum cross-sectional area in oropharynx; MDCT: multidetector computed tomography; mm: millimeter; NAV: Nasopharyngeal airway volume; OAV: Oropharyngeal airway volume; PNFW: Posterior nasal floor width; PNW: Posterior nasal width; PW: Palatal width; SNA: Sella-Nasion-subspinale angle; SNB: Sella-Nasion-supramentale angle; SNGoGn: Sella-Nasion-Gonion-Gnathion angle; TOH: Total oropharynx height; ZMLr-l: Zygomaticomaxillary lower right to left; ZMUr-l: Zygomaticomaxillary upper right to left; ZTUr-l: Zygomaticotemporal suture upper right to left.

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Table 4 Comparisons of successive measurement error between Amira and Dolphin.

		The mean absolute difference between the two consecutive scans					
		MSCT x Amira	MSCT x Dolphin	Wilcoxon signed rank test	CBCT x Amira	CBCT x Dolphin	Wilcoxon signed rank test
	Variable	Mean ± S.D.	Mean ± S.D.	*P* value	Mean ± S.D.	Mean ± S.D.	*P* value
Linear measurements on the tomographic multi-planar reformatted slice	ANW (mm)	0.6 ± 0.25	0.85 ± 0.37	0.033*	0.5 ± 0.32	0.9 ± 0.37	0.014*
	ANFW (mm)	0.37 ± 0.21	0.79 ± 0.5	0.011*	0.55 ± 0.32	0.93 ± 0.48	0.064
	PNW (mm)	0.34 ± 0.19	0.95 ± 0.45	0.014*	0.35 ± 0.25	0.65 ± 0.26	0.036*
	PNFW (mm)	0.52 ± 0.2	1 ± 0.46	0.018*	0.36 ± 0.37	0.71 ± 0.28	0.059
	EMW (mm)	0.35 ± 0.2	0.92 ± 0.59	0.014*	0.52 ± 0.44	0.8 ± 0.54	0.173
	PW (mm)	0.54 ± 0.34	0.75 ± 0.38	0.155	0.5 ± 0.22	0.63 ± 0.4	0.235
	Inter-Mpa (mm)	0.55 ± 0.38	0.89 ± 0.63	0.107	0.32 ± 0.23	0.87 ± 0.45	0.009*
	Inter-Mcf (mm)	0.21 ± 0.17	0.39 ± 0.28	0.074	0.49 ± 0.26	0.64 ± 0.34	0.096
Linear measurements on the three-dimensional surface rendering images	ZTUr-l (mm)	0.57 ± 0.18	1.08 ± 0.56	0.041*	0.48 ± 0.27	0.82 ± 0.52	0.105
	FMr-l (mm)	0.36 ± 0.24	0.52 ± 0.29	0.153	0.35 ± 0.16	0.59 ± 0.33	0.155
	FZr-l (mm)	0.33 ± 0.22	1.2 ± 0.5	0.006*	0.43 ± 0.23	1.03 ± 0.53	0.014*
	INCr-l (mm)	0.47 ± 0.2	0.96 ± 0.37	0.015*	0.31 ± 0.2	0.52 ± 0.41	0.293
	ZMUr-l (mm)	0.62 ± 0.39	1.08 ± 0.15	0.019*	0.72 ± 0.29	0.9 ± 0.58	0.557
	ZMLr-l (mm)	0.7 ± 0.32	0.93 ± 0.23	0.152	0.66 ± 0.22	0.95 ± 0.5	0.213
Measurements on the computed tomography-derived lateral cephalometric projections	SNA (degree)	0.5 ± 0.35	1.23 ± 0.93	0.037*	0.58 ± 0.35	0.69 ± 0.38	0.439
	SNB (degree)	0.68 ± 0.47	1.5 ± 1	0.025*	0.54 ± 0.31	0.91 ± 0.43	0.096
	SNGoGn (degree)	0.72 ± 0.34	1.14 ± 0.38	0.01*	0.53 ± 0.33	0.81 ± 0.5	0.124
	L (degree)	5.54 ± 4.03	5.32 ± 4.34	0.625	5.22 ± 3.29	4.59 ± 3.11	0.105
	Co-A (mm)	0.68 ± 0.16	0.55 ± 0.47	0.507	0.61 ± 0.2	0.65 ± 0.55	1
	Co-Gn (mm)	0.65 ± 0.26	0.61 ± 0.48	0.339	0.54 ± 0.3	1.32 ± 0.96	0.006*
Upper airway analysis	TOH (mm)	0.7 ± 0.16	0.81 ± 0.38	0.386	0.42 ± 0.16	0.7 ± 0.55	0.085
	IAV (mm^3)	5491.75 ± 5322.02	4808.25 ± 5289.96	0.25	4847.57 ± 3052.86	6096.86 ± 3862.18	0.75
	NAV (mm^3)	580.4 ± 548.58	918.6 ± 744.11	0.193	671.4 ± 437.92	1414.2 ± 1295.98	0.16
	OAV (mm^3)	2234.3 ± 2145.96	1793.1 ± 1043.83	0.432	3574 ± 3589.29	6097.1 ± 4616.69	0.027*
	HAV (mm^3)	871 ± 842.44	1243.2 ± 959.5	0.625	1490.6 ± 1984.64	1582.4 ± 1564.7	1
	MCA (mm^2)	28.1 ± 22.97	25.9 ± 20.86	0.919	46.9 ± 44.78	57.4 ± 56.63	0.126

*$P < 0.05$ indicates statistical significance.

Abbreviations. ANFW: Anterior nasal floor width; ANW: Anterior nasal width; Co-A: Condylion to Point A; CBCT: cone-beam computed tomography; Co-Gn: Condylion to Gnathion; EMW: External maxillary width; FMr-l: Frontomaxillary suture right to left; FZr-l: Frontozygomatic right to left; HAV: Hypopharyngeal airway volume, IAV: Intraoral airway volume; INCr-l: Inner nasal contour point right to left; Inter-Mcf: Intermolar width at the first molar central fossa level; Inter-Mpa: Intermolar width at the first molar palatal apex level; L: Lordosis angle; MCA: minimum cross-sectional area in oropharynx; MDCT: multidetector computed tomography; mm: millimeter; NAV: Nasopharyngeal airway volume; OAV: Oropharyngeal airway volume; PNFW: Posterior nasal floor width; PNW: Posterior nasal width; PW: Palatal width; SNA: Sella-Nasion-subspinale angle; SNB: Sella-Nasion-supramentale angle; SNGoGn: Sella-Nasion-Gonion-Gnathion angle; TOH: Total oropharynx height; ZMLr-l: Zygomaticomaxillary lower right to left; ZMUr-l: Zygomaticomaxillary upper right to left; ZTUr-l: Zygomaticotemporal suture upper right to left.

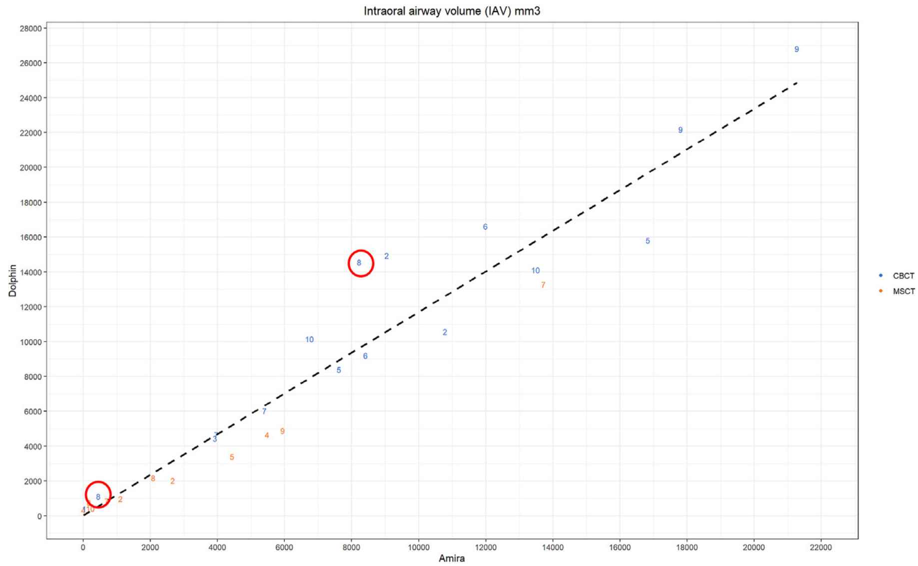

Figure 2 The scatterplot for intraoral airway volume (IAV). The color blue represents cone-beam computed tomography (CBCT) image. The color orange represents multidetector computed tomography (MDCT) or multi-slice computed tomography (MSCT). The numbers 1 to 10 represent the individual patients from 1 to 10. The black dashed line is the regression line. The red circles indicate the consecutive cone-beam computed tomography (CBCT) images of patient-8 measured by the examiner using Dolphin (y-axis) and Amira (x-axis). The successive measurement error using Dolphin is 14,558−1111 = 13,447 mm^3. The successive measurement error using Amira is 8225−454 = 7771 mm^3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

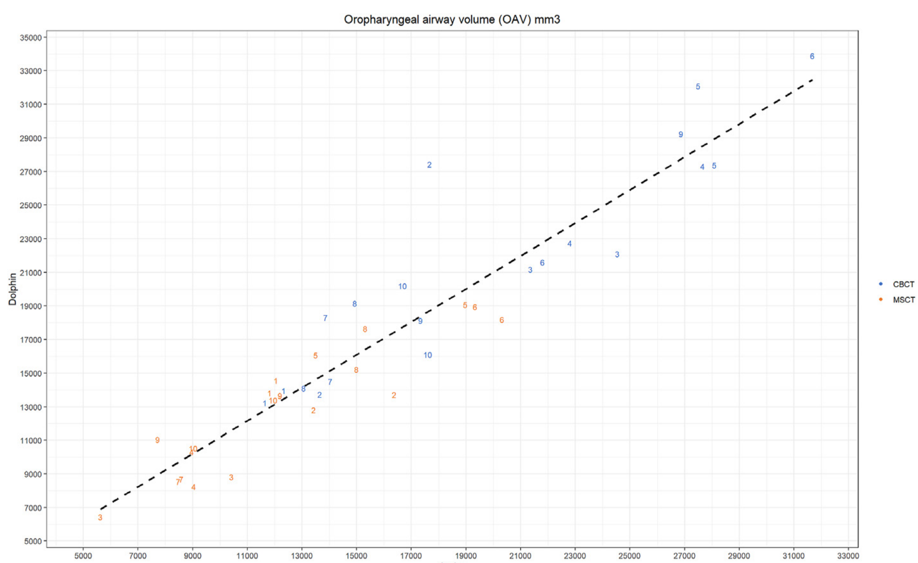

Figure 3 The scatterplot for oropharyngeal airway volume (OAV). The color blue represents cone-beam computed tomography (CBCT) image. The color orange represents multidetector computed tomography (MDCT) or multi-slice computed tomography (MSCT). The numbers 1 to 10 represent the individual patients from 1 to 10. The black dashed line is the regression line. The orange numbers are concentrated in the lower left corner, indicating that the overall measured values of MDCT group are smaller than that of CBCT group (blue numbers). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

measurements differed from MevisLab by 9∼43%, indicating the inaccuracy or unreliability of the software.[3] Amira is a software program mainly used for 3D image reconstruction, visualization and analysis. It supports data from various sources, including CT, magnetic resonance imaging, positron emission tomography, X-ray, and optical microscopy. Amira offers powerful features such as 3D data visualization, image segmentation, surface mesh reconstruction, voxel reconstruction, virtual sections, drawing, and animation. Its advantages include the ability to check

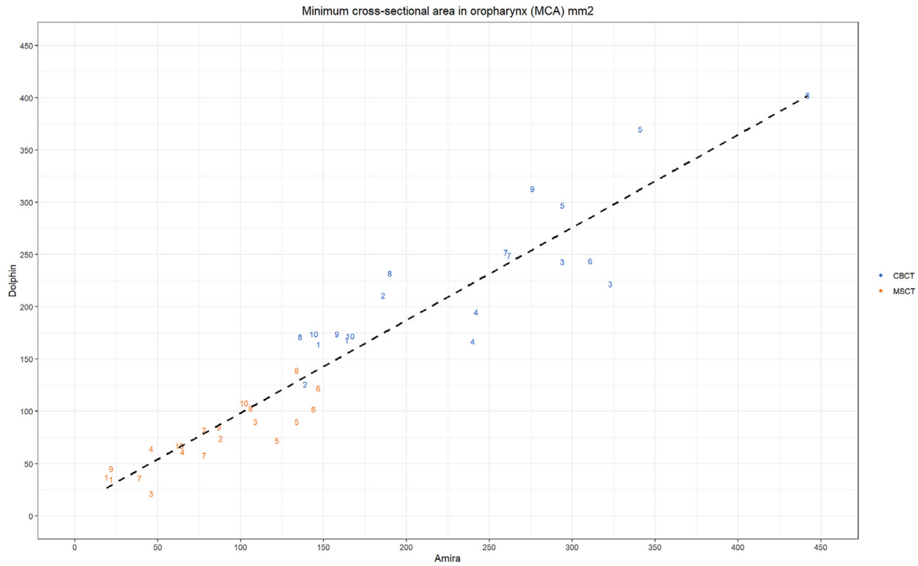

Figure 4 The scatterplot for minimum cross-sectional area in oropharynx (MCA). The color blue represents cone-beam computed tomography (CBCT) image. The color orange represents multidetector computed tomography (MDCT) or multi-slice computed tomography (MSCT). The numbers 1 to 10 represent the individual patients from 1 to 10. The black dashed line is the regression line. The orange numbers are concentrated in the lower left corner, indicating that the overall measured values of MDCT group are smaller than that of CBCT group (blue numbers). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

or adjust segmentation on different orthogonal planes (axial slice, coronal slice, and sagittal slice), automatic calculation of the minimum cross-sectional area of the airway and grayscale, and compatibility of threshold interval units with other imaging software.[36] However, it is expensive, not user friendly, and offers minimal threshold control. Unlike Amira which has a built-in HU calibration/standardization function, there are no absolute units for the threshold scale in Dolphin. When examiners subjectively choose the sensitivity threshold value for the software program to distinguish soft tissue from air by radiodensities, it may lead to poor accuracy in airway volume calculations.[13,37] This partly explains the reason why our study found that Dolphin results in greater successive measurement errors than Amira for most variables, regardless of the imaging modality. Our results are consistent with the findings of de Water et al. that Dolphin is neither accurate nor reliable for airway analysis.[3]

One limitation of this study was the retrospective design that relied on existing medical data. Although the subjects in MDCT and CBCT groups were well-matched, the within-group variabilities were still very large, as seen in the scatterplots for all variables (Appendix Figure). Since this was a retrospective study, patient-related factors such as head posture, tongue position, swallowing phase, or breathing route were not controlled. Changes in body weight or body mass index of the patients were not analyzed either. All of these could affect the airway measurements. However, our study reflected the true clinical scenario of consecutive CT imaging. Another limitation was that we only compared two different software programs. Dolphin Imaging and Amira are both paid software options used for 3D assessment. Dolphin typically costs between $3000 and $7000 USD, while Amira ranges from $10,000 to $30,000 USD, depending on the features and licensing. These programs offer advanced functionalities compared to freeware options. Free softwares like 3D Slicer, ITK-SNAP, and InVesalius, while cost-effective, may have limitations in features and user interface. Given the high costs of advanced paid software and the limitations of free alternatives, we chose to compare Dolphin and Amira to balance the need for precision with budget constraints. This approach ensures that the comparison is made with reliable and widely recognized tools for accurate 3D airway dimension assessments.

In conclusion, this study found that Dolphin software generally exhibited greater successive measurement errors compared to Amira for most linear and angular measurements of the skeleton. Particularly in CBCT airway analysis, Dolphin demonstrated considerably greater successive measurement errors, notably in oropharyngeal airway volume measurements where errors were more than three-fold higher compared to MDCT images. Given these substantial measurement errors observed during consecutive CT scanning, our findings do not support the quantitative use of CT for analyzing changes in airway dimensions in research settings. These results collectively emphasize the critical importance of software selection and highlight the need for rigorous methodological approaches to enhance the reliability of CT-based airway assessments in future studies. Therefore, when reading research articles or literature, it is essential to carefully examine the methodologies and software used to accurately interpret their findings. The significant differences observed between consecutive CT scans without any treatment intervention suggest that the reported treatment differences in research articles might not necessarily stem from the treatment itself but rather from measurement errors between consecutive scans. This underscores the need for careful software and methodology selection to obtain valid and reproducible results. Our study's findings serve as a caution against the quantitative use of 3D airway measurements in research settings. We recommend that future research considers alternative methodologies or additional validation measures to ensure the accuracy and reliability of airway assessments.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jds.2024.07.033.

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